Managing Risks to Satellite Systems from Extreme Space Weather Events

Presentation to the
Satellite Anomaly Mitigation Stakeholders' Meeting

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What am I going to try to say?

- We only know what we know, and we must try to deal with it
  - We must use what we should know
    - Humans (even engineers) are not perfect.
    - It’s hard to not make errors, especially when doing something new.
  - It can be too expensive to use all that we know
    - And Mother Nature is capricious, so we need margins
  - Our <u>models</u> for the environment are OK and getting better
  - And forecasts are essential – *Thank you, SWPC*
- We don’t know what we don’t know. We find ‘em and fix ‘em.
  - Satellites evolve in response to their environments
  - The set of “unknown unknowns” is known to exist (only)
- The solution is a balance among performance, reliability, and cost, and the right balance point depends on the customer (mostly), and we can do better, both in our designs and in our ability to forecast

Satellite Design Process

Producing a satellite is a balance among: †

Engineers, who strive for reliable, efficient designs,
Technologists, who find neat new ways of doing things,
Businessmen, who need to sell in a market at a profit,

And all of them must be respectful of

Mother Nature: She who must be obeyed.

and she doesn't reveal all her rules before the game begins:

"My god, space is radioactive." (Ray), CMOS oxide charging effects,
Spacecraft charging (multifarious), Single particle effects, …
Be confident that the set of "unknown unknowns" is not empty.

† Inspired by Rick Cook, *The Wizardry Compiled* (1989)

"Applications programming is a race between software engineers, who strive to produce idiot-proof programs, and the universe, which strives to produce bigger idiots. So far the Universe is winning."

Bad Stuff Does Happen

Image Credit: L. J. Lanzerotti, Bell Laboratories

On 20 January 1994 Canadian television, radio, telephone and scientific operations were interrupted when two communications satellites experienced operational problems within 9 hours of each other.

Anik E-1 and Anik E-2 were both GE AS-5000 models. (Heritage Lockheed Martin, so **this** won't happen again!)

The momentum wheel control circuitry in both satellites was affected. It took Telesat Canada operators 8 hours to regain control of Anik E-1 and many months to regain control of Anik E-2. The root of the problem was traced back to deep dielectric discharges within the spacecraft circuitry after many days of being bombarded by dangerous levels of high energy electrons.

How bad could it get?

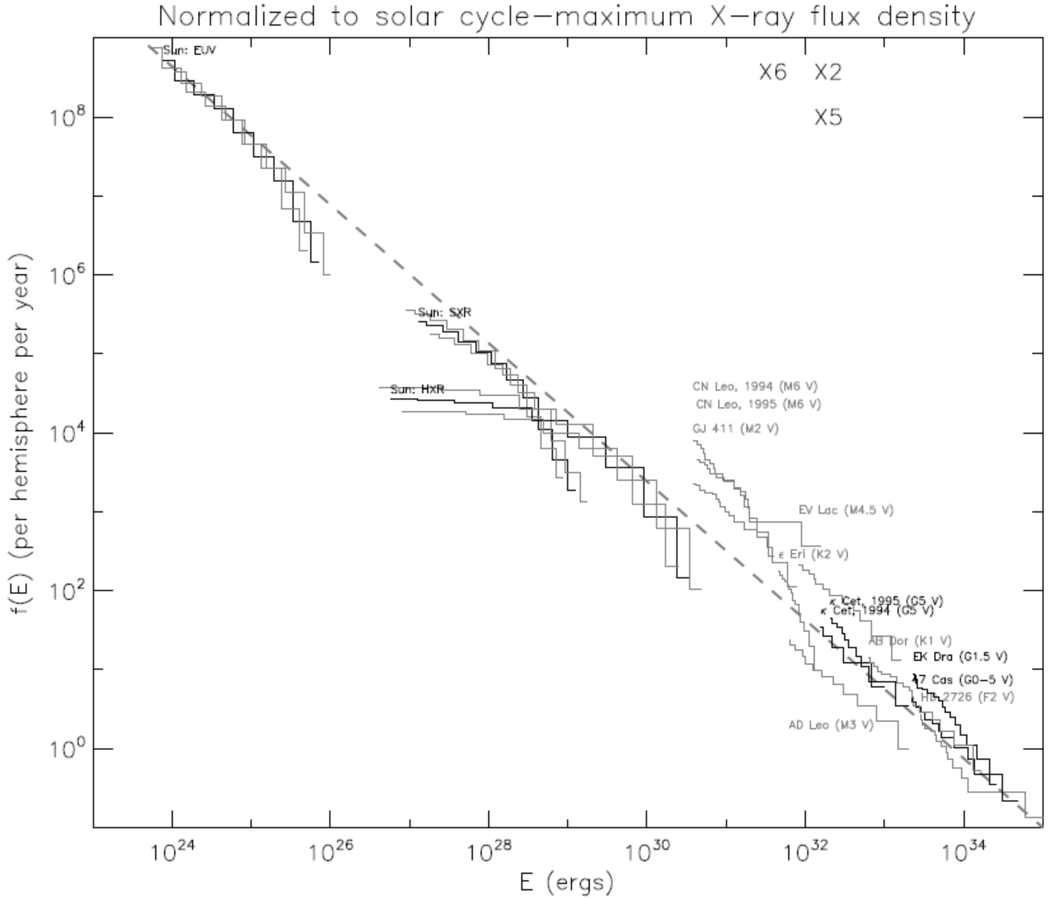


Figure 3. Downward-cumulative flare frequency distribution for energies exceeding E, normalized to approximate solar-maximum X-ray flux density levels (1.3×10^5 erg cm^{-2} s^{-1}; Judge et al. (2003)) assuming a linear dependence of the X-ray surface flux density. Flare spectra for Sun-like G-type stars are shown in black, for warmer and cooler stars in grey. The grey dashed power-law fit has an index of $\alpha_f + 1 = -0.87$. EUV data from Aschwanden (2000), soft X-ray data from Shimizu (1997), hard X-ray data > 8 keV from Lin et al. (2001), and stellar data from Audard et al. (2000). The grey histograms for solar data bracket a conservative energy uncertainty of a factor of 2. Three estimates of flare energies for GOES X flares are shown near the top, from Aschwanden & Alexander (2001) and Benz (2008).

(What is your risk tolerance?)

(How long do you need to run?)

The cumulative occurrence frequency falls by less than x10 for a x10 increase in the total energy released!

(power law index -0.87)

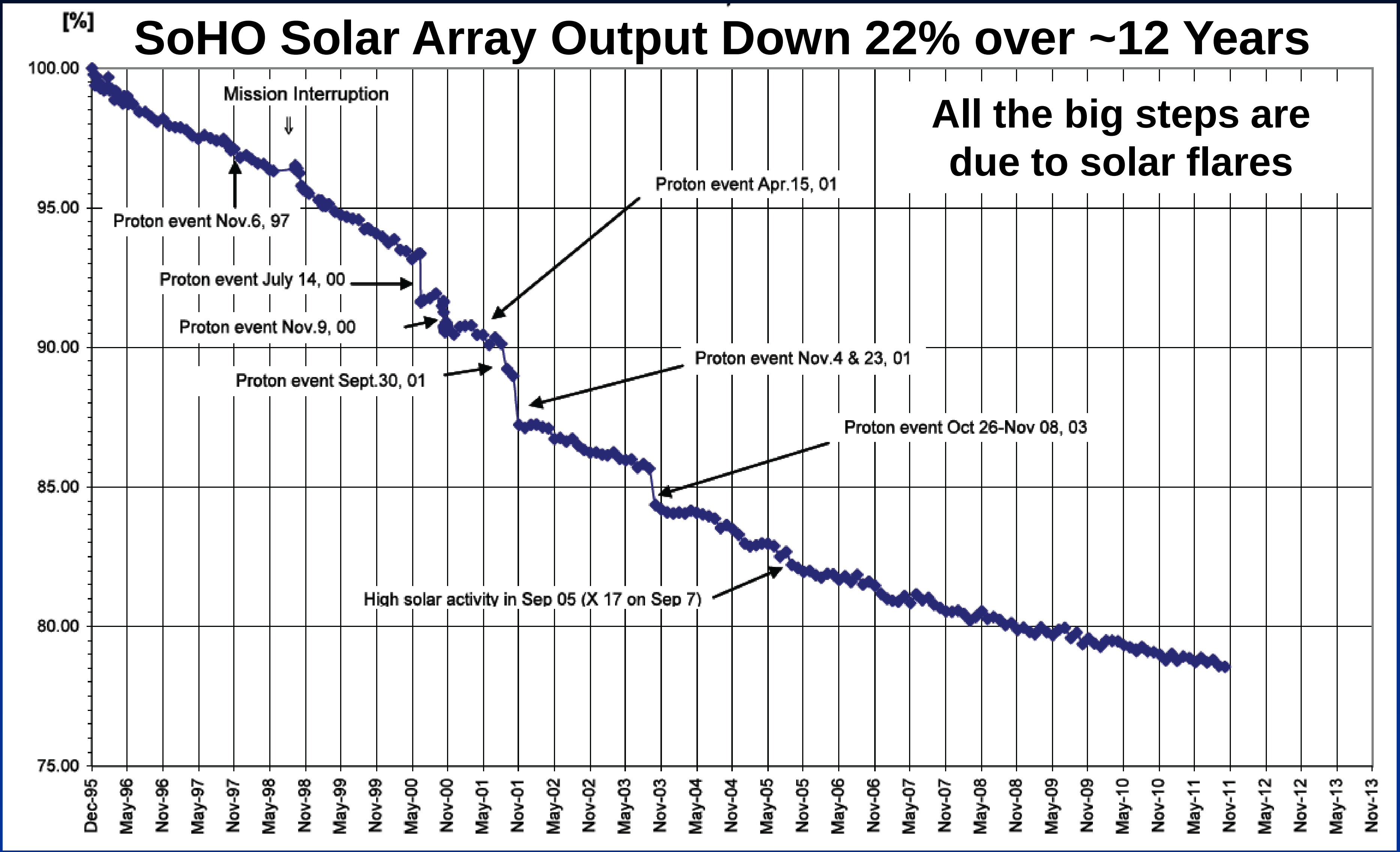
No saturation!

There is no "worst case", just a probability that a certain level will not be exceeded in some time.

Effects on Communication Satellites

- The space radiation environment is the single most significant factor in the aging of GEO comsats, limiting on-orbit lifetimes
  - Most of this is the total dose tolerance, an expendable resource
- Solar flares produce huge increases in radiation from the sun that affect the earth, moon, and interplanetary space
  - GOES-7 lost 2-3 years of lifetime in 2 days as a result of radiation damage to its solar arrays during the March 1991 solar flares
- Geomagnetic storms produce dangerous conditions (e^-, plasma)
  - Responsible for Anik E1 and E2, Tempo-2, and many more
- Space weather is responsible for ~25% of GEO satellite anomalies
  - GEO failures listed in Satellite News Digest: 23/118 = 19%
  - MILSTAR anomalies: 26%   A2100: 25%
  - Spacecraft charging anomalies dominate all but MILSTAR (none)

Space Weather Effects on a Solar Array



Space Weather Effect Categories

- **Cumulative: Bigger events shorten life more**
  - **Total dose**
    - **Premature loss of solar array power**
    - **Premature failure (to meet spec) of electronics**
  - **Some forms of spacecraft charging (maybe)**
  - **Effects integrate over mission life (linear)**

- **Transient: Sometimes, no long-term impact**
  - **Spacecraft charging and the discharges**
  - **Single-particle radiation effects**
  - **Dose rate effects**
  - **System response can be highly non-linear**

Anomalies Reveal Design Flaws *(mostly)*

- GEO comsats are designed for ~15-year lifetimes
  - "Once in a decade" conditions must be in the requirements.
  - "Once in a century" conditions probably should be in the requirements, but we may have yet to experience them.
  - So – maybe we don't know the right requirements, but we are getting along pretty well based on our experiences over the past 60 years.
- Now, when anomalies happen they reveal design flaws
  - Designs are corrected to eliminate these flaws.
  - Examples:
    - Eliminate floating conductors (associated with Anik failures)
    - A2100 solar arrays: No anomalies in last 8 vehicles, >5 years.
    - Single-particle radiation effects (EDAC, voting logic)
- How bad must it be before it can be an "act of nature"?

How are Satellites Designed to Withstand Space Weather Effects?

- **Total dose effects:**
  - **Beginning of life performance has enough margin, so that end of life performance is reached after the mission ends.**
  - **Unanticipated, large events shorten lifetime.**

- **Transient effects:**
  - **Design hardening**
    - **Make sure the effect is not fatal, and**
    - **Make sure that it doesn’t happen very often “worst-case”**
  - **Error detection and correction (EDAC, autonomous or not)**
    - **If something happens, fix it before it becomes a problem**
    - **This leads to non-linearity. If it gets bad enough, it’s real bad.**

- **Performance specs and tests start at the part level**
  - **“Worst-case” analysis predicts EOL system behavior**
  - **Analysis establishes range where EDAC will be successful**

What can we do? and How SWPC Helps.

- Total dose effects:
  - Limited options beyond just “tough it out”.
    - Configuration changes may enhance shielding of sensitive components.
- Transient effects:
  - Many transient effects are only evident if system is powered
  - Powering down may protect a system in extreme conditions
- Operators need good forecasts to make good decisions
  - Decision to implement temporary loss of service to avoid permanent loss of service (risk of system loss due to damage)
  - Enough advance warning to implement protective measures
- SWPC provides excellent forecast information
  - “Probability of event” forecasts, event nowcasts
  - Forecasts are limited both by science and by data

Summary

- Satellite builders balance performance, reliability, cost
  - MILSTAR shows we know how to build ESD-immume systems
  - Numerous examples of performance improvements as susceptibilities are identified and designed-out
- Some space weather effects can be budgeted for (dose)
  - Extreme events deplete the budget faster than planned
- Powering-down can protect some sub-systems
  - Decision to protect requires good “short-term” forecasts
- SWPC provides the best forecasts available
  - Dependant on continuing observations
  - Better forecasts would be even more valuable
    - Need better science understanding, better observations